Waves in the coastal ocean - Coastal Oceanography -

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What is a wave?

- Waves are periodic deformations of an interface
- In the ocean: surface waves (interface air-sea) or internal waves
- Wave movement (deformation of the ocean surface) propagate at speed $c$
- Particles describe oscillatory back-and-forth movements with no horizontal displacement.

A wave can be described by its:

- period $\tau$
- frequency $f = 1 / \tau$
- angular frequency $\omega = 2 \pi / \tau$
- wavelength $\lambda$
- wave speed $c = \lambda / \tau$
- wave height $H = 2A$ ($A$ = amplitude)
- wave steepness $\Delta = H / \lambda$
What generates waves?

- Meteorological forcing (wind, air pressure); sea and swell belong to this category.
- Earthquakes; they generate tsunamis, which are shallow water or long waves.
- Tides (astronomical forcing); they are always shallow water or long waves.

Ways of classifying waves: by frequency (green), by generating force (yellow), and by restoring force (blue)
Short waves

Depending on the wavelength and its relation to water depth, waves can be classified in long waves (shallow water waves) and short waves (deep water waves).

|_______________________________|________________________________|__________________ _ _ _ _ |
| 0             < λ <            2*h             < λ <            20*h         < λ |

- deep water waves or short waves
- transitional waves or long waves
- shallow water waves

Short waves: wavelength $\lambda$ is larger than twice the water depth $h$.

Longer period waves move faster than shorter period waves.

Speed: $c = \sqrt{g\lambda / 2\pi}$
Long waves

Depending on the wavelength and its relation to water depth, waves can be classified into long waves (shallow water waves) and short waves (deep water waves).

The distinction between deep and shallow water waves has little to do with absolute water depth but is determined by the ratio of water depth to wavelength.

Long waves “feel” the bottom.

Long wave speed: \( c = \sqrt{gh} \)

Wave speed is independent of their period.
Long waves (Shallow water waves)

Tides
Tsunamis
Seiches
Kelvin waves
Coastal trapped waves
Meteorological tsunamis
1. Tides

gravity exerted by the Moon and the Sun
M2 tidal amplitude

- Concept of amphidromic point
- Compare amplitude of tide in open ocean and shallow water
- Case of western Australia
- Case of east and west of UK
- Case of Gulf of Mexico and Caribbean Sea
Long waves and short waves

Phase velocity for surface gravity waves
\[ c = \sqrt{\frac{g \tanh(kh)}{k}} \]

Short waves: wavelength \( \lambda \) is small compared to water depth \( h \). \( c = \sqrt{\frac{g}{k}} \) (dispersive)

Long waves: wavelength \( \lambda \) is small compared to water depth \( h \), \( c = \sqrt{gh} \) (non-dispersive)
Amplification of the tidal wave

Tides in deep ocean travel in the form of very long Kelvin waves ($\lambda \sim 8000$km)

Over the shelf, still Kelvin wave, but slower as $h$ decreases

Consider:
$A_d$, $h_d$: amplitude of the wave in the deep ocean and depth of the deep ocean
$A_s$, $h_s$: amplitude of the wave in the shelf sea and depth of the shelf sea

$c = \sqrt{gh}$

The energy flux onto the shelf is given by $E_w c$, with $E_w = (1/2)\rho_0 g A_0^2$

As the energy must be conserved when passing from the deep ocean to the shelf sea,

$E_w c_d = E_w c_s$

Which means that the amplitude of the tide on the shelf will be related to its amplitude in the deep ocean by:

$$\frac{A_s}{A_d} = \left(\frac{h_d}{h_s}\right)^{1/4}$$

For $h_d = 4000$ m and $h_s = 100$ m, the amplitude of the tidal wave increases by a factor of $2.5$ as it enters the shelf.
Standing waves and propagating waves

**Propagating waves:** all points on the sea surface undergo periodic uplift and sinking and experience horizontal movement

→ wind waves are propagating waves

Ocean propagating waves (in the deep ocean) transport energy rather than water

**Standing wave:** oscillatory movement that doesn't create horizontal displacement

→ tides are standing waves (in the deep ocean)

Standing wave (black) resulting from two propagating waves in opposite directions (red and blue)
Standing waves in a closed domain

A progressive wave is reflected at the barrier and produces a second wave of equal amplitude moving in the opposite direction.

The two waves combine to produce a standing wave.

Nodes (zero amplitude, maximum currents) at intervals $\lambda/2$.

First node at $\lambda/4$ from the barrier.
Tides (cont'd)

- Tides are a form of low amplitude periodic motion of no consequence to the mean large-scale oceanic circulation. **Standing waves** → video Making_standing_waves.mp4

Video: is this a standing wave? (surfing a standing wave on the North Shore.mp4)

Propagation and amplitude influenced by friction, the rotation of the earth (**Coriolis force**), and **resonances** determined by shape and depth of ocean basins and marginal seas.

- In many shallow seas, tidal movement, though still periodic, is no longer weak, and can result in mean water movement known as the **residual flow**.

- Smaller water bodies such as marginal seas or estuaries cannot produce a response to astronomical tidal forcing. If there is tidal movement in these regions, it is **forced by the tidal currents of the deep ocean** which enter and leave the region periodically at the connection to the ocean: **co-oscillation tides**

- Depending on the size of the sea or bay they take the shape of a seiche or rotate around one or more amphidromic points.
**Tidal resonance**

In narrow bays we found nodes (the non-rotating equivalent to amphidromes)

At the open entrance of the bay: the standing wave with the bay must match the ocean tide

Tidal response of a narrow gulf
Tidal resonance

At the mouth of a bay of length $L$, bay tidal amplitude and ocean tidal amplitude must match:

$$A_0 \sin \omega t = A_{sw} \cos kL \sin \omega t$$

Therefore the amplitude of the standing wave in the bay will be:

$$A_{sw} = \frac{A_0}{\cos(kL)} = \frac{A_0}{\cos(\frac{2\pi L}{\lambda})}$$

If $L = \frac{\lambda}{4}$, the denominator of this equation goes to 0 $\rightarrow$ amplitude goes to $\infty$ $\rightarrow$ RESONANCE

In practice, $A_{sw}$ will not be $\infty$ because of friction and tidal currents modifications due to topography.

The length of the Bay of Fundy is $\sim \frac{\lambda}{4}$ for the main lunar tide (M2) $\rightarrow$ a single node near the ocean boundary.

Tidal range in the Bay of Fundy is the largest in the global ocean ($\sim16$ m at spring tides)

Similar resonant responses will also occur in bays with a length close to $3 \frac{\lambda}{4}, 5 \frac{\lambda}{4}, 7 \frac{\lambda}{4} ...$
Tide resonance in the Bay of Fundy

http://www.bayoffundy.com
Tides in the Mediterranean Sea

- Very small amplitude because of the narrow connection with the open ocean (Gibraltar Strait)
- Predominant mode: M2

Lozano and Candela, Oceanologica Acta, 1995

Source: http://aviso.altimetry.fr
Tides in the North Sea: co-oscillation tides

- Red lines are co-phase lines of the M2 tide, labelled in hours after the moon’s transit through the meridian of Greenwich

- Blue lines give the mean tidal range at spring tide (co-range lines of the sum of M2 and S2)

- Describe how the tide propagates in the North Sea

- Concept of tide age

- What is the depth in the North Sea at the two blue crosses?

North Sea range <3 m
Point 1:
~ 1 degree/h (30 m/s)
Depth of 90 m

Point 2:
¼ degree/h (7.6 m/s)
Depth of 6 m
- The amplitudes and phases of co-oscillation tides depend on the closeness of a resonance frequency to one of the tidal frequencies and on the amplitude of the tidal currents in the deep ocean at the connecting line with the marginal sea.

Bay of Fundy, Canada, tidal range > 15 meters

**Ocean basin resonance frequency**

The size (width, depth) of a basin determines the time it takes to a tide to reach its end point.

If this time is similar to the most important tidal constituent (or a multiple), the tide amplitude can be reinforced by reflections of the tide at the entrance and end point of the basin.
Diurnal/semi-diurnal/mixed tides: depends on topography, coast orientation, shelf width
**Tidal components**

**Semidiurnal**

Principal lunar semidiurnal  \( M_2 \)  12.42h
Principal solar semidiurnal  \( S_2 \)  12h
Larger lunar elliptic semidiurnal  \( N_2 \)  12.66h

**Diurnal**

Lunar diurnal  \( K_1 \)  23.93h
Lunar diurnal  \( O_1 \)  25.82h
Solar diurnal  \( P_1 \)  24.06h

**Higher Harmonics**

Shallow water overtides of principal lunar  \( M_4 \)  6.21h
Shallow water overtides of principal solar  \( S_4 \)  6h

- **full or new moons**  -> gravitational forces of both the Sun and Moon are in phase  ->  **spring tides** (vives-eaux)
- **Half moon**  -> **Neap tides** (mortes-eaux)
- The **largest annual tidal** range can be expected around the time of the **equinox**, if coincidental with a spring tide  (perfect alignment)
S = Sun
E1 = Earth at perihelion (January 2nd)
E2 = Earth at aphelion (July 2nd)
M1 = Moon at perigee
M2 = Moon at apogee

Aphelion (July 2)

E2

Perigee

94.5 million miles
91.5 million miles

Common projection of the Earth's orbital plane around the Sun (the ecliptic) and the Moon's orbital plane around the Earth.

Earth's Orbit

Perihelion (Jan. 2)

Moon's Orbit

Apogee

M1

M2
Equilibrium tides

Figure 8.6

High latitudes: diurnal tides

Midlatitudes: mixed tides

Low latitudes: semidiurnal tides
Diurnal, semi-diurnal and mixed tides
Large tidal range → always associated with **strong tidal currents**

Tidal currents on the shelf always larger than tidal currents in the open ocean.

In some locations tidal currents can become unusually strong even under a moderate or small tidal range. This occurs where constrictions prevent the free flow of the tidal wave and force it to rush through narrow openings.
Saltstraumen, Saltfjord, northern Norway, currents up to 41 km/h (11.4 m/s !!!)

- 500 m deep fjord, connected with North Atlantic Ocean by a 3 km long channel of only 150 m width and 31 m depth. The channel is too small to allow the fjord to follow the oceanic tide, and the difference in water level between the two ends of the channel can reach up to 1 m → formation of whirpools (maelstroms) of 10 - 15 m diameter.

- For centuries it has been said that the Saltstraumen runs strongest on Good Friday (the Friday before Easter). This is easily understood from tidal theory: the Christian church sets the date of Easter as the first Sunday after the full moon following the vernal equinox: by definition the tide generating potential of the sun and moon act in concert at that time.
On June 14, 2002, these four industrial cranes, valued at approximately $1.25 million each, arrived in San Francisco Bay from Shanghai, China. Designed to rapidly hoist 40-foot-long containers from super-sized cargo ships, they had to be transported beneath the Oakland Bridge to reach their final destination, the Port of Oakland. The tidal range of San Francisco Bay when these cranes were transported was 1.3 m and the bridge had a motion of approximately 0.1 m. With detailed knowledge of the tidal cycle and skilful piloting of the vessel, the cranes cleared the bottom of the bridge by about 1.8 m.

Source http://oceanservice.noaa.gov
Tides and fishing

- Shallow seas close to **resonance** with one of the tidal periods → great importance for the world's fishing industry.
- **Strong tidal currents** → **turbulence** → entire water column **well mixed** through the year
- **Nutrients are continuously kept in suspension.**
- These coastal seas are therefore among the most **productive fishing regions** of the world ocean, rivalling the great coastal upwelling regions and the fertile Southern Ocean.
- The North Sea or the Newfoundland Banks are two examples of regions where tidal mixing keeps nutrient concentrations in the water column at a high level.
Sudden changes in water depth → from a standing wave to a propagating wave

- **propagation speed of shallow water waves depends on the water depth**
- propagation speed slower over the shallower region than over deeper region: mismatch speed
- **part of the wave continues** as a propagating wave in the shallow water,
- **part of it is reflected** back into deep water and combines with the incoming wave to form a partially standing wave

Effect of a sudden change of bottom topography on tides.

A wave approaching a step-like depth change from the deep water (h₁) side is partly reflected at the step and continues partly as a propagating wave into the shallow water (h₂) side.

The amplitude of the reflected wave is given by the reflection coefficient \( a \), the amplitude of the wave which passes into shallow water by the transmission coefficient \( b \).

\[
a = \frac{1 - \sqrt{\frac{h_2}{h_1}}}{1 + \sqrt{\frac{h_2}{h_1}}} \quad b = \frac{2}{1 + \sqrt{\frac{h_2}{h_1}}}
\]

If \( h_1 = h_2 \) the wave passes without reflection \( (a = 0, b = 1) \).

If \( h_1 \) and \( h_2 \) are different \( (h_1 > h_2) \) → \( b > 1 \); the amplitude increases in shallow water, because wave speed \( c \) depends on the water depth: \( c = \sqrt{gh} \)

If \( h_2 = 0 \) → total reflection \( (a = 1) \).
Tidal bores (mascaret)

A tidal bore can result from the arrival of the tidal wave to an estuary

- Changes in depth and/or topography
- Shoaling and narrowing estuary: decreases speed and increases amplitude of tidal wave
- Shorter rising tide than falling tide
- Extreme: rising tide can take on the form of a wall of water which travels up the estuary → a nearly instantaneous rise of water level is formed as the water wall passes: tidal bore

Qiantang River, China

Cook Inlet in Girdwood, Alaska

Video tidal_bore.mp4
Extracting energy from tides

Rance tidal power station
Tidal amplitude of 14 m (before the construction of the power plant)
600 GWh/year (~70 MW) – 0.012 % of France's power demand

Environmental impact:
Change in tidal flow
Some fish species have disappeared
Silting reduces 1% of capacity / year
Turbine in the Bay of Fundy

Installed in November 2016

16 m diameter, generates 2MW of energy (2 to be installed)

Environmental concerns: impact to tidal range, fish population, sediments dynamics
2. Tsunamis

Long waves generated by earthquakes, landslides, volcanic eruptions...

Tsunami means "harbour wave" in Japanese

What is the speed of a tsunami in deep water? (~ 4000m)

What happens when the wave reaches shallow water?

Passage of the tsunami of 26 December 2004 as seen in a sea level record from the Seychelles. Data from the Seychelles Meteorological Office.
Tsunami warning systems

Example: Deep-ocean Assessment and Reporting of Tsunami (DART), NOAA

To ensure early detection of tsunamis and to acquire data critical to real-time forecasts

Stations located in zones with potential for tsunami generation
**How do they work?**

- An anchored seafloor bottom pressure recorder (BPR)
- A companion moored surface buoy for real-time communications (acoustic link)
- Temperature and pressure at 15-second intervals → sea surface height
- Two way communication between buoy and tsunami warning center: buoys can be set up in “event” mode preventively
3. Seiches

Standing waves in closed or semi-closed basins

Longest period (back and forth):

$$T = \frac{2L}{\sqrt{gh}}$$

L is the length of the basin

A first order seiche in an open basin

A second order seiche
Waves propagating along a coast

In the **open ocean**, the basic balance of forces is that of geostrophy (balance between the horizontal pressure gradient and the Coriolis force)

A current in the northern (southern) hemisphere has the high pressure on its right (left): eddies

In the **coastal ocean** high and low pressure centres do not have to be surrounded by uniform pressure on all sides, but can "lean against the coast".

A current can flow along the isobars only on one side of the pressure centres

Transport of water from one side of the pressure centre to the other (lowering and rise of sea level)

Waves move along the coast: **Kelvin waves**
4. Kelvin waves

Only felt in ~ 100km from the coast

Period: from several days to a few weeks

Generated by an abrupt change in the wind field

Can occur also at the Equator (Coriolis force acts in opposite directions in both hemispheres)
- Equatorial Kelvin waves
- Faster than coastal Kevin waves

Do not need the presence of a sloping shelf

adapted from Houghton and Beer (1976)
5. Coastal trapped waves

Only appear when a shallow area exists between the coast and the deep ocean (slope)

Cannot exist at the Equator

Result from variable wind blowing over the shelf \(\rightarrow\) periodic upwelling and downwelling at the coast

Below the Ekman layer: periodic onshore and offshore movement of the entire water column

In a sloping shelf: water column gets shorter and thicker/ longer and thinner with onshore-offshore movements \(\rightarrow\) change in angular momentum
Effect of variable wind stress on the coastal ocean

Northward wind stress → downwelling → pushes water below the mixed layer away from the coast.

Southward wind stress → upwelling → pulls the water below the mixed layer towards the coast.

In which hemisphere takes place this diagram?
Propagation of coastal trapped waves along the Indian Ocean coast of Australia as seen in sea level records for July, 1997

Large traveling disturbances generated in the Indian Ocean

First seen at Hillarys (Perth).

Propagate south-eastward

Reach Bass Strait (Lorne and Stony Point) and Tasmania (Burnie) within three days.
6. Meteorological tsunamis

A tsunami-like wave (long wave), originated by a meteorological cause.

- Air pressure disturbances are mostly the cause: intense low pressure systems, tropical storms, hurricanes...

http://ichep.blogspot.be/2006/06/rissaga-ciutadella.html